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MEASUREMENTS OF RADIOACTIVE AIR FROM BACTERIAL LEACHING OF URANIUM STOPES

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by

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ABSTRACT

Bacterially-assisted leaching provides a relatively inexpensive and simple way of recovering uranium from mined-out stopes or low-grade uranium ores in some Canadian underground uranium mines. A study was conducted to characterize the radioactivity environment of a typical mined-out uranium stope where uranium was being recovered by bacterially assisted heap-leaching of muck brought down by drilling and blasting operations. Measurements were carried out on radon gas and its progeny, thoron progeny, and air flow through the stope during several experimental phases of the leaching operation. In addition, the residence time of radioactive air in the leaching stope during the aeration operation was determined by several methods. Values in excess of 70, 7 x 10^5 Bq/m^3 and ~0.1 were obtained for the radon progeny Working Level, radon gas concentration, and thoron progeny Working Level, respectively. The air residence time in the stope was in the range 28-39 h depending on the method used. The experimental results indicate that the radiation data are consistent with a stope model with a discrete, non-continuous source of radon gas, such as that corresponding to a uranium leaching operation, rather than the more conventional extended, continuous source model.

Key words: Uranium leaching; Bacterial leaching; Uranium stope; Radioactivity; Underground uranium mines.

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MESURE DE L'AIR RADIOACTIF PROVENANT DE LA LIXIVIATION BACTÉRIENNE DANS LES CHANTIERS D'ABATTAGE DU MINERAI D'URANIUM

par

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RÉSUMÉ

La lixiviation bactérienne constitue une méthode relativement peu coûteuse et simple de récupérer l'uranium dans les chantiers d'abattage déjà exploités ou dans les minerais pauvres en uranium de certaines mines d'uranium souterraines au Canada. On a effectué une étude pour caractériser l'environnement radioactif d'un chantier typique de minerai d'uranium déjà exploité où l'uranium était récupéré par lixiviation bactérienne en tas des déblais produits par les opérations de forage et de sautage. Les mesures ont porté sur le radon et ses produits de filiation, sur les produits de filiation du thoron et sur l'air traversant le chantier d'abattage pendant plusieurs phases expérimentales de lixiviation. En outre, on a déterminé à l'aide de plusieurs méthodes le temps de séjour de l'air radioactif dans le chantier d'abattage où avait lieu la lixiviation, pendant l'opération d'aération. Des valeurs supérieures à 70, 7 x 10^5 Bq/m^3 et ~0,1 ont été obtenues pour le niveau de travail des produits de filiation du radon, pour la concentration de radon et pour le niveau de travail des produits de filiation du thoron, respectivement. Le temps de séjour de l'air dans le chantier d'abattage variait de 28 à 39 heures selon la méthode utilisée. Les résultats expérimentaux indiquent que les données de rayonnement concordent avec un modèle de chantier comportant une source de radon discontinue, comme celle qui correspond à l'extraction par lixiviation, plutôt qu'avec le modèle plus traditionnel comportant une source étendue et continue.

Mots clés : Extraction de l'uranium par lixiviation; lixiviation bactérienne; chantier d'abattage du minerai d'uranium; radioactivité; mines d'uranium souterraines.

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INTRODUCTION

Heap leaching is an extractive process used as a means of recovering uranium from low grade uranium ores. Heap leaching is in relatively widespread use in some underground uranium mines in Elliot Lake (Ontario, Canada) to partially recover uranium in low grade ores contained in previously mined stopes (1,2).

Because uranium leaching is best carried out in situ, and in partially enclosed inactive stopes, elevated radiation levels are produced during uranium leaching operations which may affect other working locations. For this reason it is important to characterize and quantify the radioactive atmosphere produced in the leaching stopes, and to determine the radioactivity leaking out from these stopes by natural and/or forced ventilation into working environments.

The leakage of radioactivity from partially enclosed stopes into adjacent mine spaces is determined by two processes, namely, diffusion and transport phenomena. Diffusion processes arise from concentration gradients whereas transport phenomena are related to air flow exchange between the stope and the adjacent space environment. It therefore follows that migration of airborne radioactivity is highly dependent on the ventilation characteristics of the leaching stope, a measure of which is the residence time and the clearance time. These ventilation variables play an important role in the dynamic behaviour of radioactivity in partially enclosed spaces.

This work presents a study on the airborne radioactivity characteristics of a production test stope at Denison Mines Ltd. assigned to the recovery of uranium by bacterially-assisted heap leaching by water flood ing methods. It also presents data for the stope air residence time as determined by purely radioactivity techniques based on measurements of radon

gas, ^{222}Rn, concentration, and the radon progeny Working Level, WL(Rn), by gas chromatography tracer gas techniques using SF_6 as a tracer gas, and by conventional anemometry.

BACKGROUND INFORMATION

Details on the uranium leaching operation are given elsewhere (1-3). The following is a simplified description of the process for the reader's benefit.

Bacterial leaching of uranium ores is based on the oxidation of the insoluble tetravalent uranium oxide UO_2 into the leachable hexavalent uranium sulphate UO_2SO_4. This oxidation is mediated by ferric ions, Fe^{3+}, which are generated in turn by oxidation of ferrous ions (Fe^{2+}) in pyrites, which often accompany uranium ores, by the bacterium Thiobacillus ferrooxidans (Tf).

The flood leaching process consists of flooding a well aerated stope with water containing the bacterium Tf in order for the chemical oxidations to proceed. After flooding the stope(s), the resulting uranium-leachate is drained for further processing. Stope aeration is accomplished by compressed air through pipes connected to an air distribution system running along the floor of the stopes.

The flooding and draining operations were conducted by means of a pump-assisted piping system.

The flood leaching cycle proceeds as follows:

1. The stopes are drilled and blasted to ensure that enough fragmented ore is available for the leaching operation;
2. A bulkhead is built to contain the water added to the stopes for flooding purposes:
3 Compressed air is injected into the stopes for a period of time to ensure adequate aeration for the oxidation of Fe^{2+} to take place;

4. The stopes are flooded with water containing a liquid solution of the bacteria Thiobacillus ferrooxidans. The flooding process lasts for about one week;
5. The stopes are drained in order to separate the liberated oxidized uranium salt from the pyritic uranium ore. The drainage operation takes about one week;
6. The leaching cycle is initiated again starting at item 3.

The aeration/flooding/draining operations last altogether about 3.5 weeks.

Flood leaching is carried out in some experimental stopes in a specifically designated area of the mine. For this purpose leaching blocks are 'prepared'. A leaching block consists of two adjacent stopes connected by slots through the common rib pillar.

The approximate stope dimensions are 70 m long, 12 m wide, and 3 m high. The volume of the stope was about 3×10^3 m^3. Inside each stope three air lines are laid consisting of perforated polyethylene pipe protected by perforated steel pipe casing and a layer of muck. The air lines are fed from the mine's compressed air system from either the bottom or both top and bottom of the stope.

Sealing of the leaching reactor vessel, i.e., stope, is done by erecting a pressure bulkhead isolating the haulage access to the stope. No access is possible to the stope after the retaining pressure bulkhead is in place. An exhaust for aeration is provided by boreholes to each stope drilled from a ventilation drift above the stope.

Because of uranium extraction from the ore in the leaching process, high radiation levels in the bulkheaded stope(s) are to be expected. Furthermore, significant radiation level changes between the aeration, flooding and draining operations should also be expected.

Figure 1 shows a three dimensional cut-away of a stope of a typical flood heap leaching block (4).

THEORETICAL BACKGROUND

The build-up of radon gas in an underground uranium mine enclosure of volume V (m^3) where no air exchange occurs can be described by the expression:

$$\frac{dN}{dt} = k - N\lambda \qquad \text{Eq 1}$$

where N represents the radon atom concentration in the volume V. i.e., atom/m^3, and λ is the radon radioactive decay constant (2.1×10^{-6} s^{-1}). The variable k represents the radon emanation rate from the walls of the enclosure (atoms/m^3s).

The solution to Equation 1. subject to the boundary condition $N(t = 0) = N_0$. is given by:

$$N(t) = \frac{k}{\lambda}(1-e^{-\lambda t}) + N_0 e^{-\lambda t} \qquad \text{Eq 2}$$

Equation 2 can be written in terms of activity concentration (atoms/s m^3) using the well-known expression:

$$A = N\lambda \qquad \text{Eq 3}$$

If air exchange at a rate Q(m^3/s) in V is allowed to take place. Equation 1 must be modified to take into account the removal of ^{222}Rn from V due to ventilation, in addition to radioactive decay:

Hence.

$$\frac{dN}{dt} = k-N\left(\frac{Q}{V} + \lambda\right) = k-N\Lambda \qquad \text{Eq 4}$$

where.

$$\Lambda = (Q/V) + \lambda \qquad \text{Eq 5}$$

The ratio $(Q/V)^{-1}$ is known as the air residence time. or $t_R = V/Q$.

The solution of Equation 4 can easily be obtained subject to the

boundary condition $N(t = t_1) = N(t_1)$. The symbol t_1 represents the time during which the condition Q=0, i.e., no air exchange in V, is maintained. It also represents the time at which air flow in V is initiated.

If no constant supply of radon is available, i.e., k = 0, Equation 4 reduces to:

$$dN/dt = -N\Lambda \qquad \text{Eq 6}$$

The solution of Equation 6 is given by Equation 7:

$$N(t) = N_0 e^{-\Lambda t} \qquad \text{Eq 7}$$

where $N_0 = N(t = 0)$.

Equation 6 and its solution, Equation 7, describe the radon gas evolution in the stope after the stope has been drained to separate the liberated oxidized uranium salt from the host rock. Part of the radon gas formed is dissolved in the aqueous solution (uranium leachate) and is removed during the draining operation whereas the rest of the radon gas is released from the solution, before and during draining, into the air volume of the stope. In Equation 7, N_0 represents the number of ^{222}Rn atoms in V at the end of the draining operation under no air flow conditions, i.e., Q = 0. (It has been assumed that the contribution to the generation of ^{222}Rn from the stope walls is small compared to the liberation of ^{222}Rn from leaching operations).

It is not difficult to show from Equation 7, after some manipulation, that:

$$\ln 0.5 = -\Lambda t_{50} = -(\lambda + Q/V)\, t_{50}$$

or $$0.693 = (\lambda + 1/t_R)\, t_{50}$$

Hence,

$$t_R = \frac{t_{50}}{0.693 - \lambda t_{50}} \qquad \text{Eq 8}$$

where t_{50} is the time at which the radon activity is reduced to half of its original value.

Similar arguments apply equally well to the radon progeny Working Level, WL(Rn), because of its relationship to the radon gas concentration, $[^{222}Rn]$, through the so-called F-factor, defined by $F = WL(Rn)/[^{222}Rn]$. The F-factor will remain constant if meteorological, environmental and air flow conditions remain constant. These conditions determine, amongst other things, the plate-out characteristics of the stope for the radon progeny. Hence, if F is known and constant conditions prevail, WL(Rn) can also be used to determine t_R.

The variable t_R is usually determined by conventional anemometry. If the volume of the stope, V, is known and air flow conditions, Q, are measured it follows that:

$$t_R = V/Q \qquad \text{Eq 9}$$

Tracer gas techniques using SF_6 as a tracer gas and gas chromatography with an electron capture detector are more accurate than anemometry for the evaluation of t_R in complex air flow systems and difficult experimental situations. This technique, and other techniques, are well-established and have been used extensively for many years in research related investigations and ventilation studies (5-9). The continuous tracer gas method consists of injecting SF_6 into, say, the stope, at a given constant flow rate until steady-state conditions are reached, i.e., measured SF_6 concentration, $[SF_6]$, at the stope exhaust remain constant. At this point, the source of SF_6 is removed and the SF_6 concentration versus time is followed. From the concentration decay curve, the residence time can be determined as the time elapsed for $[SF_6]$ to decrease to 50% of its original value.

EXPERIMENTAL PROCEDURE AND APPARATUS

Boreholes were drilled in the wall of the stope, opposite the bulkhead, for monitoring purposes. Two boreholes per leaching block were drilled, i.e.,

one borehole for each stope of the block. A length of plastic pipe, about 1.5 m in length and approximately 10 cm internal diameter, was driven partially onto a short length of metal pipe fitted to one of the boreholes.

Several sampling ports were located along the plastic pipe to monitor radon gas, ^{222}Rn, radon progeny Working Level, WL(Rn), thoron progeny Working Level, WL(Tn), tracer gas (SF_6) concentration, air flow, and some meteorological variables such as temperature and humidity. (See Figure 2.)

An anemometer was fitted snugly to the end of the pipe. The plastic pipe was terminated by an open-ended wooden box housing a small radon progeny Working Level continuous monitor, model alphaPRISM, manufactured by alphaNUCLEAR (Toronto, Canada), facing the air stream.

A sampling port located in the plastic pipe permitted continuous monitoring of radon gas by means of a radon gas monitor, model AB-5/EL, manufactured by Pylon Electronic Development (Ottawa, Canada). An adjacent sampling port allowed WL(Rn) and WL(Tn) measurements by grab-sampling.

Most of the above radiation and meteorological variables were monitored continuously during the duration of the test: usually, a measurement was taken every 60 minutes or 100 minutes.

The operational procedure was as follows. The stope was aerated for a period of time after which the compressed air supply was turned off for 48 hours to allow the radiation level to build up and reach a near equilibrium state. The compressed air supply was then turned on and maintained constant during the remainder of the tests.

Experiments were conducted shortly after the stope was drained from a previous leaching operation. The tests were of two weeks duration. Radiation levels, air flow, SF_6 concentration levels, and other relevant data were plotted versus time and compared with theoretical models. The data permitted a relatively detailed study of the dynamics of the system. It also allowed

estimation of the air residence time by radioactivity, anemometry and tracer gas techniques.

EXPERIMENTAL RESULTS AND DISCUSSION

Radon progeny Working Level, WL(Rn), and thoron progeny Working Level, WL(Tn), measurements by grab-sampling techniques are given in Table 1. Radon gas concentration, i.e., [^{222}Rn], WL(Rn), and air flow rate, Q, measurements by continuous monitoring methods are shown in Figures 3 and 4. It should be noted that, for the sake of simplicity, a great deal of experimental data collected during the two-week stope leaching monitoring program have been omitted. Hence, only data showing dynamic and/or steady-state conditions of interest, and data useful for the calculation of the air residence time, have been included. (Note: [^{222}Rn] in Figure 3 is given in counts per hour (cphr). To obtain pCi/L and Bq/m^3 multiply by 2.33 x 10^{-3} pCi L^{-1}/cphr and 0.084 Bq m^{-3}/cphr, respectively.)

WL(Rn) and WL(Tn) grab-sampling measurements started the day after injection of pressurized air into the leaching stope. The data obtained for the first day (May 27, 1986) show that WL(Rn) and WL(Tn) had already reached a maximum value (see Table 1). An approximate 10-fold decrease in WL(Rn) was measured from May 27th to May 30th. However, the average value for WL(Tn) during the same period of time only decreased by a factor of about 3 (see Table 1). An increase in both WL(Rn) and WL(Tn) was observed on June 2nd which corresponds to the tail of somewhat elevated values of these two variables observed during the weekend by continuous monitoring. After this transient increase, both WL(Rn) and WL(Tn) returned again to their 'normal' steady-state values, i.e., WL(Rn) ~7-8, and WL(Tn) ~0.3-0.4. The reason for this transient effect is not clearly understood but does not seem to be related to significant changes in air flow conditions in the stope.

Figure 3 shows that shortly after injection of air into the stope, WL(Rn) increased rapidly reaching a maximum value of ~70 WL in about 22 h. It then decreased rapidly at first and then more slowly, until eventually a steady-state value was attained after a few days. During the same period of time [^{222}Rn] followed a similar pattern.

The first portion of Figure 3 shows the effect of injecting compressed air into the leaching stope via the air distribution system. The time elapsed between the start of air injection and the time at which maximum values for [^{222}Rn] and WL(Rn) are attained provides a measure of the retention time of airborne radionuclides in the rock heap, i.e., the time taken by the carrier gas (compressed air) to remove radon and its progeny from the interstitial spaces in the heap. The decay portion of the graph is a measure of the residence time. Both retention time and residence time depend on air flow conditions in the leaching stope.

Calculation of retention and air residence times can be done with both radon gas concentration, [^{222}Rn], and WL(Rn), as these two variables are related by the so-called F-factor as indicated above. From experimental data collected, the value for the F-factor in the leaching stope was in the range 0.2 to 0.3.

From Figure 3 and Equation 8, the values obtained for the residence time, t_R, were in the range 34 to 39 h depending on the variable and time chosen for the measurements.

It should be noted that there is some uncertainty regarding the above values for the residence time as it has been calculated assuming a discrete and non-continuous source of radon gas, see below and (3). This assumption is partly supported by:

a) the very low ratio WL(Tn)/WL(Rn), as shown in Table 1;

b) the stope where leaching operations were conducted was a mined-out

stope, and hence, of very low ore grade.

In all likelihood, the residence time calculated here should be modified somewhat in order to take into account the contribution from the extended, continuous radon source from the mine walls and pillars.

Figure 4 provides further support for the hypothesis of radon gas (dissolved in water or in the gas-phase) being 'trapped' in the void spaces of the rock heap. Under normal circumstances, and for a uniform, extended, and continuous source of radon, an increase in the air flow through the stope should bring about a decrease in [^{222}Rn] and WL(Rn), followed by steady-state conditions (3). However, Figure 4 shows a transient behaviour similar qualitatively, although somewhat different quantitatively, to that of Figure 3 when the air flow is suddenly increased.

The detailed analysis of the data of Figure 4 is beyond the scope of this paper. These data illustrate, and partly support, the notion of radon in the gas-phase and radon dissolved in water, being trapped in the interstitial void spaces of the uranium-depleted rock heap, which is released by the flow of passing compressed air.

The experimental data of Figures 3 and 4, and the low values for the ratio WL(Tn)/WL(Rn) (= 0.01 - 0.1) (see Table 1) are not consistent, as discussed elsewhere (3), with the predictions of a mine (or stope) model with a uniformly distributed and continuous ^{226}Ra/^{222}Rn source, and an air flow and gram ratio ^{238}U/^{232}Th in the range measured in Elliot Lake underground uranium mines. The data are, however, consistent with an 'enriched' ^{238}U discrete source such as that corresponding to a uranium leaching operation, and hence, a localized, non-continuous, source of ^{222}Rn.

It should be noted that by continuous source is meant the continuous generation of ^{222}Rn by decay of ^{226}Ra. A non-continuous source might imply:

a) Sudden injection of ^{222}Rn into the stope;

b) Abnormally high, and transient, build-up of ^{226}Ra or ^{222}Rn by artificial means. This would correspond to the case of extraction of ^{238}U from the ore, by leaching processes. Aqueous solutions of ^{226}Ra and ^{222}Rn, formed during extraction, and ^{222}Rn in the gas-phase, can easily be trapped in the spaces between the crushed ore-bearing rock making up the leaching heap.

The high [^{222}Rn] and WL(Rn) backgrounds observed in the 'empty' stope under steady-state conditions or periods of rest(see Figures 3 and 4 and Table 1) are not consistent with the low uranium ore grade in the rock formation and experimental air flow conditions (~0.016 - 0.03 m^3/s) in the stope. This contention is further supported by the unusually low ratio WL(Tn)/WL(Rn) (~0.01 - 0.1), which is in the order of ~0.5 - 1.0 for most other locations in the mine. The high backgrounds observed were due to an undertermined volume of uranium leachate still remaining in the stope after the draining operation.

Figure 5 shows SF_6 gas concentration measured at the exhaust of the stope versus time for a continuous SF_6 tracer gas injection mode. The first portion of the curve shows the build up of gas followed by a steady-state condition characterized by a constant SF_6 concentration. The decay portion of the graph corresponds to the removal of the SF_6 source. The decay portion of the curve permits the residence time of the air in the stope to be determined by reading the time elapsed for the SF_6 concentration to be reduced to 50% of its original maximum value. The value obtained by gas chromatography using SF_6 as a tracer gas and grab-sampling techniques was 33.5 h (4). Air residence time determined by conventional anemometry gave a value of about 28 h (4).

Comparison between the values obtained for the air residence time by radioactivity, anemometry, and tracer gas techniques shows that there is fairly good agreement between the radioactivity method (34-39 h) and the

tracer gas method (33.5 h), the former being only slightly higher (<17%) than the latter. Anemometry, on the other hand, gave the lowest value (~28 h) for the air residence time in the leaching stope.

An issue still remains outstanding, namely, the radioactivity contribution from the leaching stope into other mine locations during the aeration and uranium leachate draining operations. Values for the rate of release and total release of radioactivity into adjacent working locations from the leaching stope can be calculated with sufficient approximation to be suitable for practical purposes as shown below.

Taking the maximum values of WL(Rn) and [^{222}Rn] observed during the leaching operations, i.e., WL(Rn) ~70 and [^{222}Rn] ~7 x 10^5 Bq/m^3, and the values measured for the air flow rate Q (~0.016 m^3/s), and the volume of the stope V (~3 x 10^3 m^3), the following values for the rate of release of activity, m*, are obtained:

$$m^*(WL(Rn)) = 70 \times 20.53 \times 0.016 \sim 23\ \mu J/s\ (\sim 8.3 \times 10^4\ \mu J/h),$$

where, 1 WL(Rn) = 20.53 μJ/m^3; and

$$m^*(^{222}Rn) = 7 \times 10^5 \times 0.016 \sim 1 \times 10^4\ Bq/s\ (\sim 4 \times 10^6\ Bq/h).$$

A similar calculation for the total release of radioactivity, m, gives:

$$m(WL(Rn)) = 70 \times 20.53 \times 3 \times 10^3 \sim 4.3 \times 10^6\ \mu J, \text{ and}$$

$$m(^{222}Rn) = 7 \times 10^5 \times 3 \times 10^3 \sim 2.1 \times 10^8\ Bq.$$

From the above data, a rough value for the time of total removal of activity ($t = m/m^*$) from the stope can be calculated as ~50 h.

It should be noted that the values calculated above for m* are substantially higher than the real values because dilution effects have been ignored. These values are, therefore, conservatively high and represent an upper limit.

A simple calculation using the above radioactivity data shows that the contribution of radioactivity to adjacent mine locations, i.e., a large mine

drift in our case, from the stope was not significant. This is so because the stope exhaust flow rate was 2-3 orders of magnitude lower (Q ~0.016 m^3/s) than the air flow rate in the drift (>10 m^3/s).

A rough value for the total amount of radon gas dissolved in the uranium leachate can be obtained from the total volume of leachate (~3 x 10^3 m^3) and [^{222}Rn] measurements in the leachate. The value is ~1 x 10^6 x 3 x 10^3 = 3 x 10^9 Bq.

CONCLUSIONS

The experimental data presented here show the following features of interest:

a) high radon gas concentration: [^{222}Rn] ≥2.0 x 10^4 pCi/L (7.4 x 10^5 Bq/m^3);

b) high radon progeny concentration, i.e., WL(Rn) ~70 (maximum value);

c) high radon gas concentration in drainage water: ≥2.9 x 10^4 pCi/L (1.07 x 10^6 Bq/m^3) (3);

d) increase in [^{222}Rn] and WL(Rn) after injection of compressed air followed by a decrease of these variables with increasing time until a steady-state condition is attained; and

e) very low ratio WL(Tn)/WL(Rn) ≤0.1.

Items a) to d) are consistent with a stope model with a discrete, non-continuous, radon source similar to that corresponding to a uranium leaching operation where an 'enriched' ^{238}U discrete source is produced in the extractive process, as in the experimental case investigated here.

Air residence time determined by three different techniques gave values in the range 29-39 h, the lowest value corresponding to anemometry and the highest value corresponding to radioactivity measurements. Tracer gas and ratioactivity determinations agreed reasonably well and within <17%.

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Table 1 - Radon progeny and thoron progeny grab-sampling data at the flood leaching stope.

Date	Time	Sample No.	WL(Rn)	WL(Tn)	WL(Tn)/WL(Rn)
May 27/86	9:30	1	76.78	0.74	0.010
	10:11	2	57.00	0.83	0.015
	10:53	3	56.40	0.85	0.015
	12:07	4	66.58	1.59	0.024
	12:44	5	62.26	2.50	0.040
			(63.80)	(1.30)	(0.020)
May 28/86	8:15	1	37.57	0.55	0.015
	8:55	2	39.47	0.62	0.016
	9:55	3	34.21	0.85	0.025
	10:35	4	29.17	0.93	0.032
	11:47	5	24.78	0.86	0.035
	12:28	6	31.11	1.27	0.041
			(32.72)	(0.85)	(0.026)
May 29/86	10:10	1	10.84	0.44	0.040
	10:51	2	10.03	0.49	0.049
	11:32	3	10.20	0.50	0.049
	12:12	4	9.80	0.53	0.054
			(10.22)	(0.49)	(0.048)
May 30/86	9:04	1	7.61	0.39	0.051
	9:48	2	7.19	0.41	0.057
	10:42	3	7.16	0.41	0.057
	11:47	4	7.03	0.55	0.078
	12:26	5	7.94	0.56	0.070
			(7.39)	(0.46)	(0.063)
June 2/86	9:39	1	11.18	0.52	0.046
	10:20	2	7.68	0.48	0.062
	10:57	3	10.72	0.49	0.046
	11:59	4	10.55	0.64	0.061
	12:56	5	10.37	0.77	0.074
			(10.10)	(0.58)	(0.057)
June 3/86	7:36	1	8.44	0.44	0.052
	8:15	2	8.55	0.48	0.056
	9:14	3	8.18	0.45	0.055
	10:20	4	8.25	0.43	0.052
	11:02	5	7.97	0.40	0.050
	12:05	6	8.16	0.45	0.055
	13:04	7	7.63	0.40	0.052
			(8.17)	(0.44)	(0.053)

Cont. overleaf

Table 1 - continued

Date	Time	Sample No.	WL(Rn)	WL(Tn)	WL(Tn)/WL(Rn)
June 4/86	7:18	1	7.29	0.44	0.060
	8:21	2	7.25	0.40	0.055
	9:18	3	7.51	0.41	0.054
	10:29	4	7.22	0.42	0.058
	11:19	5	7.04	0.45	0.064
	12:24	6	6.78	0.44	0.065
	13:26	7	7.44	0.75	0.100
			(7.22)	(0.47)	(0.065)
June 5/86	9:40	1	6.67	0.37	0.055
	10:29	2	6.62	0.33	0.050
	11:24	3	6.39	0.35	0.055
	12:30	4	6.69	0.32	0.048
			(6.59)	(0.34)	(0.052)

Note: the values in brackets represent daily average values.

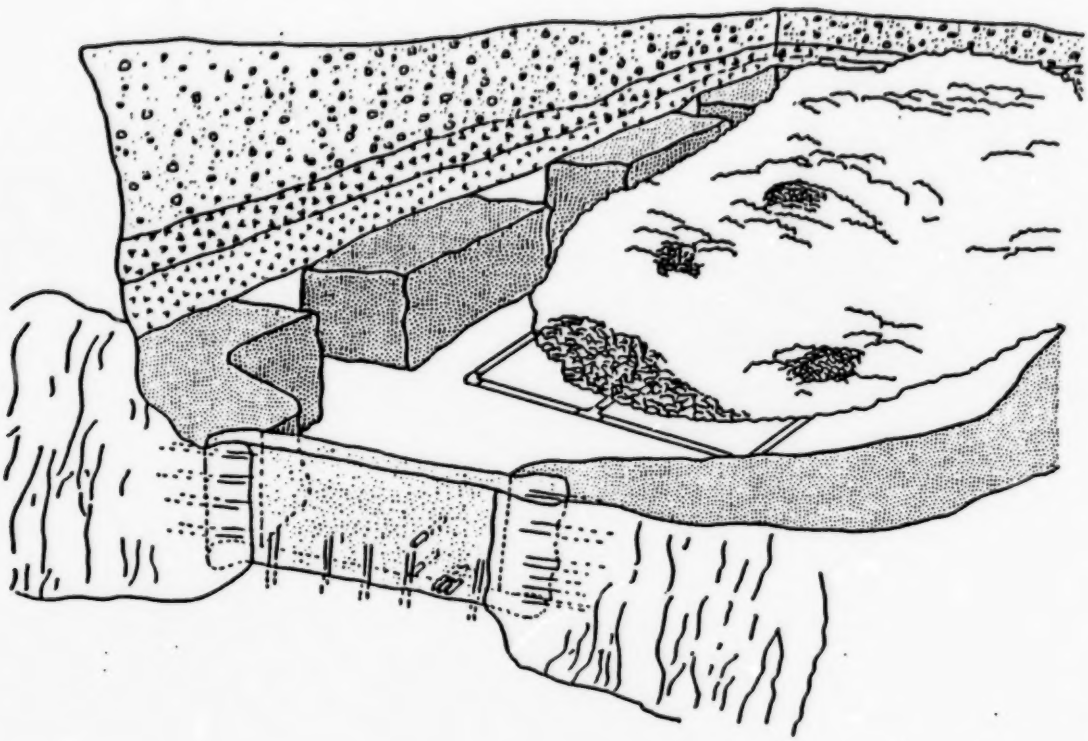

Fig. 1 - Three-dimensional cut-away of the leaching stope (ref. 5).

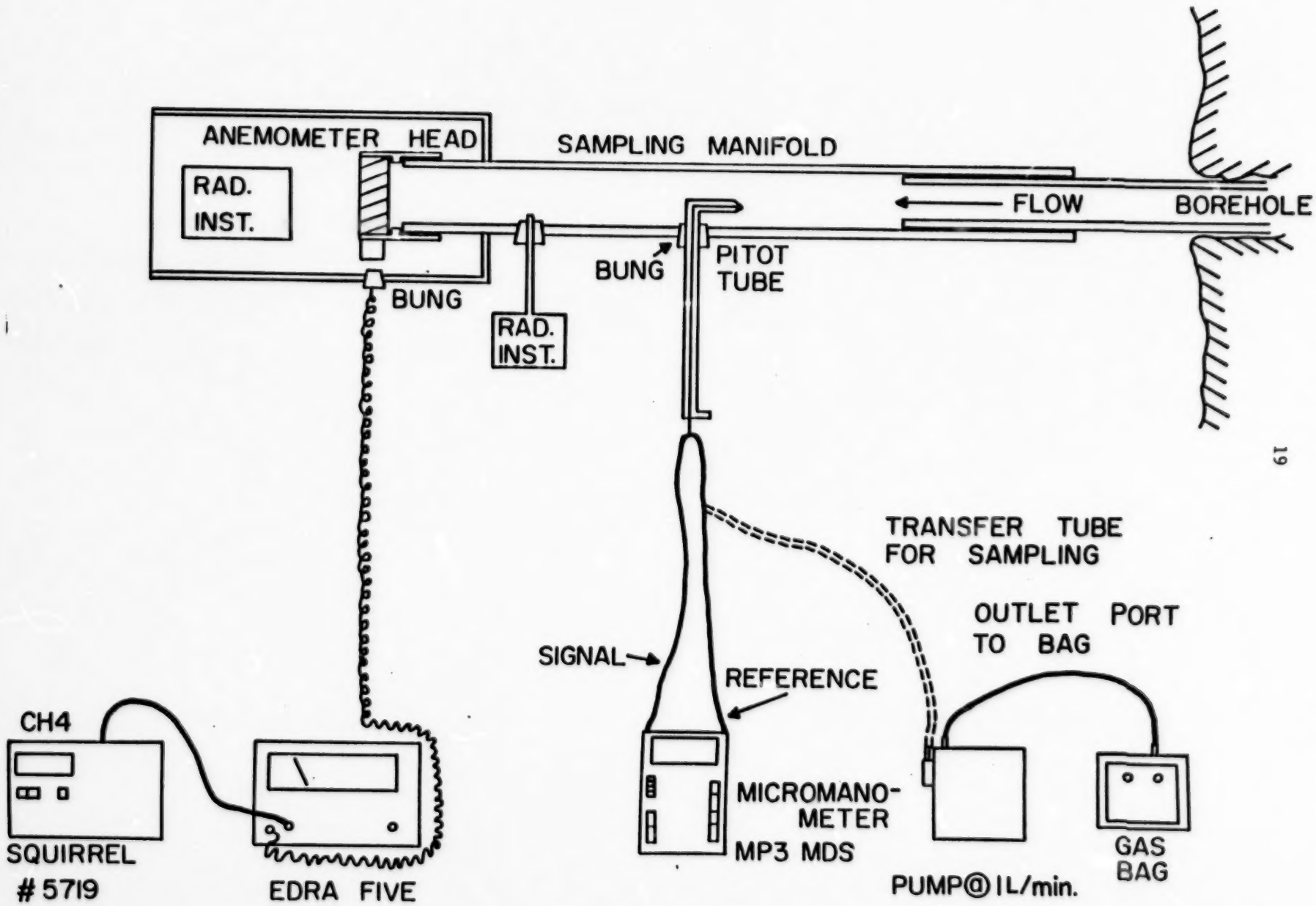

Fig. 2 - Experimental arrangement of sampling station. (Note: Rad. Inst. stands for radiation instruments).

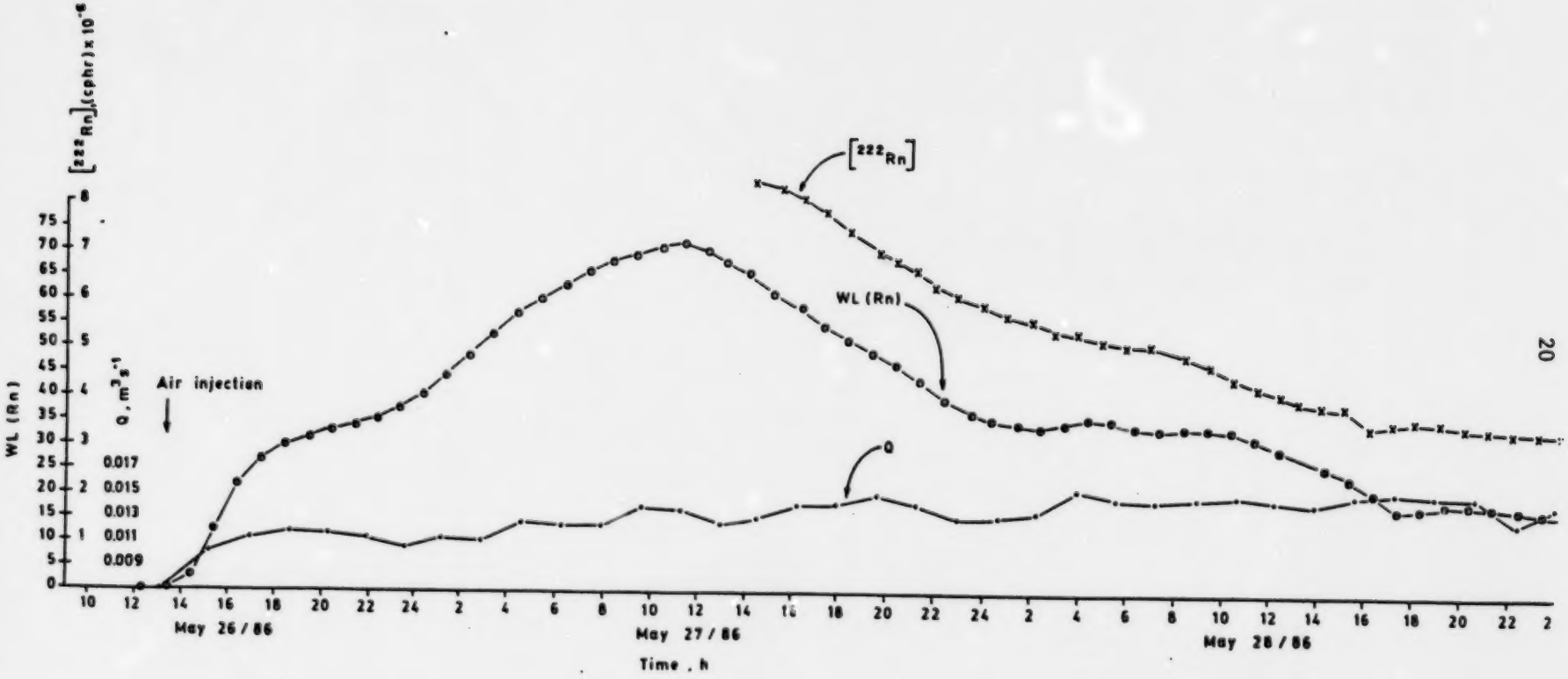

Fig. 3 - Radon progeny Working Level, WL(Rn), radon gas concentration, [^{222}Rn], and airflow, Q, versus time in leaching stope after injection of air.

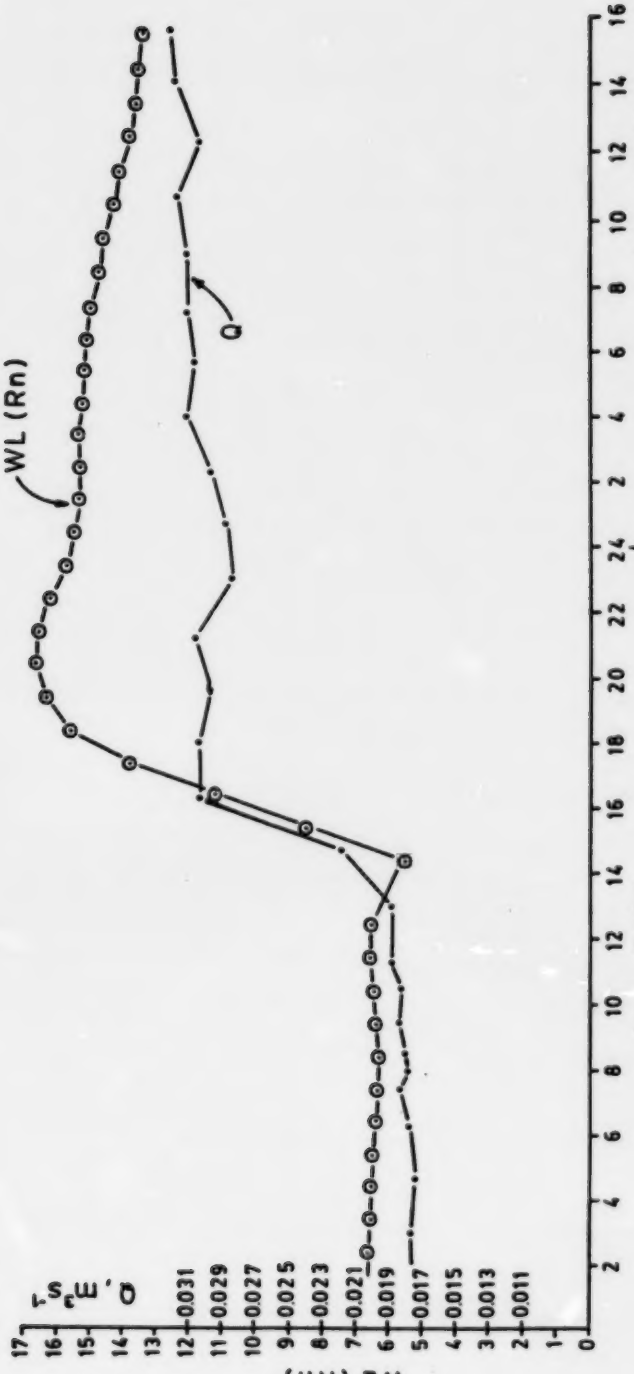

Fig. 4 - Radon progeny Working Level, WL(Rn), and airflow, Q, versus time.

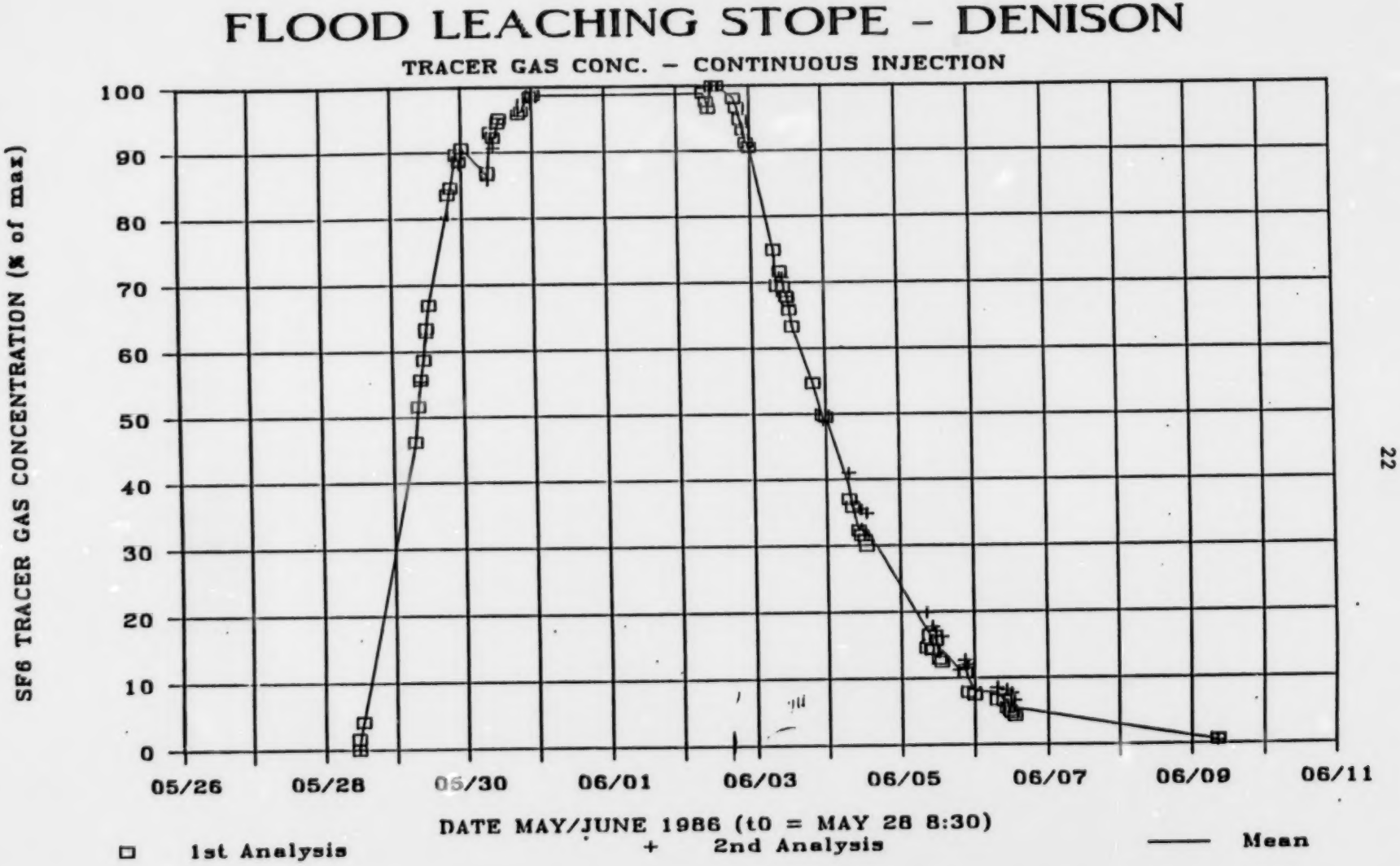

Fig. 5 - Tracer gas concentration - continuous injection.